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Original Research

Influence of Słup Dam Reservoir on Flow and Quality of Water in the Nysa Szalona River

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Abstract

After a flood in 1997 that affected the basin of the upper and central Odra River (on selected dam reservoirs, including drinking water reservoirs), the operational water fill ordinates were lowered in order to increase the flood capacity of the reservoirs. One of these reservoirs is the Słup. Its main functions include: compensation of water outflow from the Nysa Szalona and flood protection. This paper presents the analysis of flows of the Nysa Szalona River below and above the Słup Reservoir, analysis of the water table and reservoir capacity, plus quality assessment of water flowing in and out of the reservoir, including stored water. Water quality assessment was based on analyses of the following parameters: NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, BOD_5, COD_{Mn}, DO, Cl^-, SO_4^{2-}, TOC, electrolytic conductivity, water temperature, and TSS. The study shows that in the period of 2005-08 the reservoir significantly compensated flows in the Nysa Szalona River. Significant relationship between the volume of water flowing out of the reservoir and volume of water flowing into the reservoir was observed (statistical significance at the level of $p<0.05$). A statistical analysis of linear correlations among all investigated water quality indicators at particular measurement points was also carried out. Significance of differences among some average water quality indicators with regard to inflowing and outflowing water was found. In order to protect the Słup Reservoir from pollution, construction of a pre-dam in the reservoir backwater is proposed.

Keywords: dam reservoir, river, water flow, water quality, pre-dam

Introduction

One of the main functions of dam reservoirs is the accumulation of water in overflow periods and its release in water-deficient seasons [1]. They serve economic needs, provide drinking water and contribute to flood protection. They are also used for energy, navigation, natural, and recreational purposes [2-4]. Despite their various functions, the operation of dam reservoirs can be smooth and easy, provided that certain conditions are fulfilled.

Dam reservoirs in Poland, in the basin of the upper and central Odra River, that include potable water reservoirs have been playing a significant role in flood protection, particularly since the flood in 1997 [5-7]. In reservoirs such as the Nysa on the Nysa Kłodzka River, the Mietków on the Bystrzyca River and the Słup on the Nysa Szalona River, flood capacity was increased by lowering the operational water fill ordinate. Similar actions were undertaken in Saxony (Germany), in the basin of the Elba River after the flood in 2002 by increasing the flood capacity in potable water reservoirs [8].

Another function of dam reservoirs is the improvement of surface water quality. It is estimated that dam reservoirs can temporarily retain up to 90% of the total inflowing pollutant load, depending on water retention time, reservoir depth and inflow loads [9]. There is still no common answer to the question whether hydrotechnical construction deteriorates or improves the quality of water. Generally, it

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has been observed that big reservoirs are able to improve the quality of the receiving waters with slight or average pollution levels. However, various opinions still exist as to how water quality is changed by the water retention in the reservoir [1, 9-16].

Proper management of the water in dam reservoirs is very important for the management of outflows beneath the reservoirs. What should be taken into consideration here, for example, are hydrological and meteorological monitoring in the reservoir catchment and in the reservoir, as well as at the reservoir outlet, the monitoring of water quality at the inlet and outlet of the reservoir, and proper water management in the reservoir during its normal operation or during a flood emergency period and, finally, proper construction and maintenance of the reservoir [7]. Moreover, in order to retain clean water in the reservoir proper, good water and wastewater management in the reservoir catchment must be endeavored [17].

The aim of this study is to analyze the influence of the drinking water dam reservoir Słup on the flow and water quality in the Nysa Szalona River. The following analyses were made: of the Nysa Szalona river flow above and below Słup Reservoir, of the water table levels, and a budget analysis of the reservoir, namely, volume, inflows, and outflow. Particular attention is being paid to the water feeding the reservoir, which is important from the point of view of proper operation of the reservoir. In order to protect the Słup Reservoir, the construction of a pre-dam in the reservoir's backwater area is proposed.

Study Site

The Słup Reservoir (51º5'58.11"N 16º6'30.07"E) (Fig. 1) was constructed in 1978 by separation of the Nysa Szalona Valley (tributary of the Kaczawa River) at 8.200 km of the water course. The area of the reservoir catchment is 382 km^2. The Słup Reservoir is administered by the Regional Water Management Board in Wrocław. The main functions of the reservoir are: compensation of outflows in the Nysa Szalona River and its recipient, the Kaczawa River, to provide enough water for Legnica and KGHM Polska Miedź S.A. at the water intake from the Kaczawa River in Przybkowo; and flood protection below the reservoir. The reservoir is situated in the village of Słup, municipality of Męcinka, Lower Silesia Voivodeship, in southwestern Poland (Fig. 1).

The normal reservoir parameters are: normal fill-level temporarily lowered, i.e. operational fill-level – 174.00 m a.s.l. (24.31 mln m^3, 318 ha), normal fill-level – maximum operational fill-level – 176.00 m a.s.l. (31.52 mln m^3, 408 ha), max. fill-level – 177.60 m a.s.l. (38.69 mln m^3, 486 ha). The capacity of the reservoir at the highest maximum damming (178.05 m a.s.l.) is 40.93 mln m^3, and the fill-area – 505 ha [18]. The reservoir consists of a bowl, surface spillway, bottom gate, front earth dam, and small water power plant.

Methods

Research carried out in 2005-08 included:

- Analysis of the water flow volume in the Nysa Szalona River above and below the reservoir and analysis of the water table fill levels and volume of water stored in the reservoir. Average daily values of these parameters were obtained from [19];
- Water quality analysis for the Nysa Szalona River flowing to the Słup Reservoir (In_res, stream-km 14.1), water flowing out of the reservoir (Out_res) and water stored in the reservoir (W_res), Fig. 1. Water quality analyses in 2005-07 were performed by the Voivodeship Inspectorate of Environmental Protection in Legnica. At the In_res measurement point 23 water samples were collected, and at W_res and Out_res – 9 samples, respectively [20]. Additionally, in the 2007-08 my own water quality analyses were carried out.

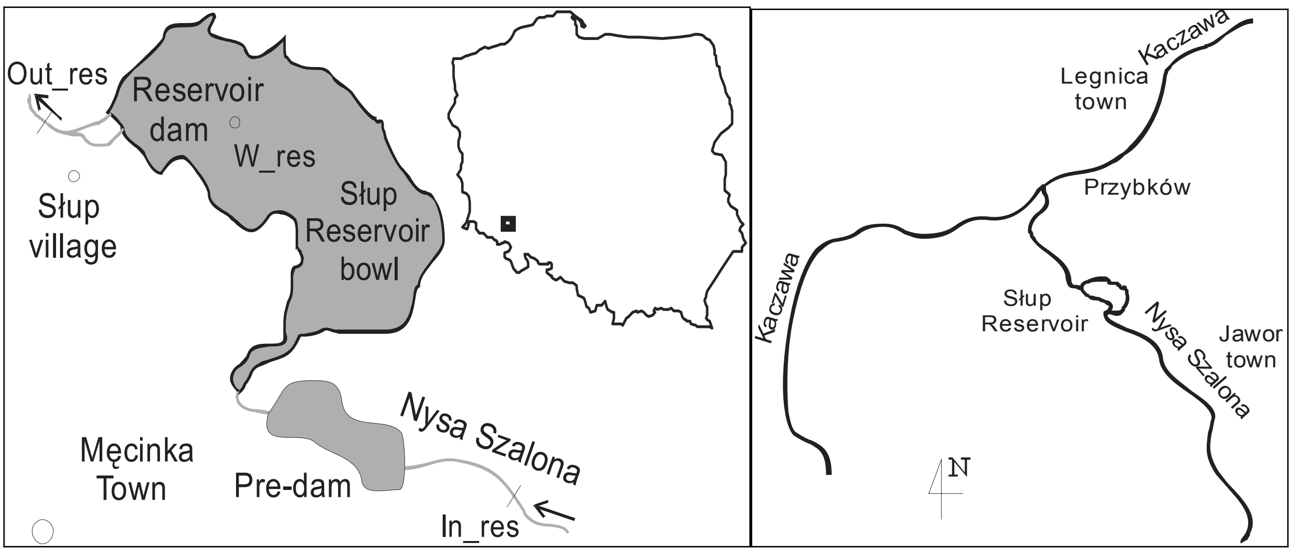

Fig. 1. Location of the Słup Reservoir on the Nysa Szalona River, including a future pre-dam and water sampling points for physicochemical analyses.

At each of the 3 measurement points 10 water samples were collected and water quality analysis was performed. The following parameters were analyzed: nitrate NO_3^-, nitrite NO_2^-, ammonia NH_4^+, phosphate PO_4^{3-}, BOD_5, COD_{Mn}, dissolved oxygen DO, chlorides Cl^-, sulfates SO_4^{2-}, total organic carbon TOC, electrolytic conductivity, water temperature, and total suspended solids TSS. The quality of water flowing out of the reservoir was assessed according to the Ordinance of the Polish Ministry for the Environment of 27 November 2002 on requirements for surface waters used for consumption [21]. The Polish ordinance is in accordance with Directive 75/440/EEC.

To assess the differences between the quality parameters of water flowing to the reservoir, water stored in it and water flowing out of the reservoir, the STATISTICA program was used. All statistical analyses were preceded by normality tests for distribution of the analyzed variables [22]. To check whether the samples come from population of a normal distribution W Shapiro-Wilke's test was applied. For all parameters various descriptive statistical properties are computed such as the average arithmetic mean, including a confidence range determining the range around $\alpha=0.05$. As a dispersion measure an interval and standard deviation of the mean are assumed. The analysis also includes the computation of correlations between 24-hour cumulative water inflow to the reservoir (In_res) and 24-hour outflow from the reservoir (Out_res), as well as correlations between concentrations of all water quality indicators at particular measurement points. The statistical description of the correlations is made using Pearson's correlation coefficient and linear regression [23]. The correlation coefficient r is a measure of rectilinear relationship between two or more variables. It was generally assumed that the correlation was statistically significant if $p<0.05$. In order to check the significance of differences between average values of water quality indicators in the case of water flowing into the reservoir and water flowing out of it, a t-Student test for independent samples was applied at the significance level of $p<0.05$. The zero hypothesis for individual mean values of investigated indicators at the inflow and outflow was rejected if statistically significant differences between them occurred.

Results and Discussion

Hydrology

From the point of view of water management in the Słup Reservoir and the outflows beneath it, information on water table levels in the reservoir is very important. In the analyzed period (January 2005-December 2008) the normal operational fill level defined in the Guidelines [24] as 174.00 m a.s.l. was exceeded in the period of 1-5 April 2006 (174.16), in the period of 9-12 August 2006 (174.22), and in February 2007 (by 26 cm), (Fig. 2). The elevated fill levels in the reservoir were caused by thawing snow (February and April) and rainwater flowing to the reservoir (August), (Fig. 3).

In the investigated period the average water fill ordinate (172.43 m a.s.l.) was lower than the operational fill ordinate 174.00 m a.s.l. The average volume of water stored in the Słup Reservoir was 19.68 mln m^3. According to the available literature [3, 9, 10, 12, 27], a characteristic feature of dam reservoirs is large fluctuations of the water level, which results in uncovering the major reservoir bottom. What is also very important here is that fluctuations of the water table in reservoirs may appear in very short time and several times within the year. In many reservoirs this obstructs the development of a littoral zone, which could constitute a barrier for capturing substances flowing to the catchment [10, 12]. The amplitude of water table fluctuations in the Słup Reservoir in 2005-08 was 4.33 m (Fig. 2).

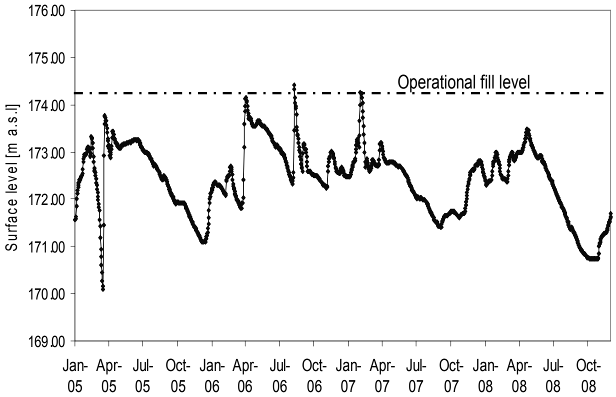

Fig. 2. Daily water fill ordinates in the Słup Reservoir in 2005-08.

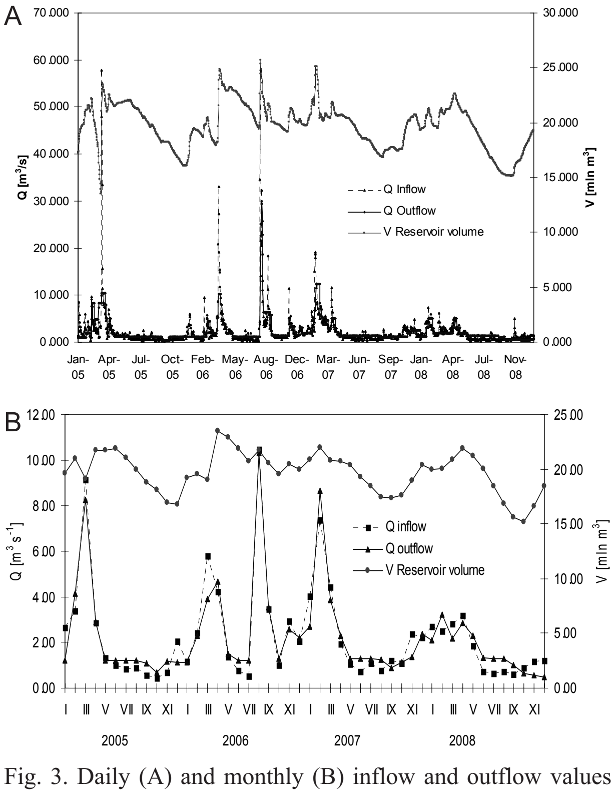

Fig. 3. Daily (A) and monthly (B) inflow and outflow values and the volume of the Słup Reservoir in 2005-08.

The analysis of water inflows in the Słup Reservoir section presented in Guidelines [24] showed that the average annual discharge (SSQ) was 2.13 $m^3 \cdot s^{-1}$ (for 1949-83).The analysis of the amount of water flowing to the reservoir indicates that in the period of 2005-08 the average water inflow was 2.265 $m^3 \cdot s^{-1}$1. This may testify to a slight increase of water reserves in the reservoir catchment in the investigated period. The lowest inflow was recorded on October 4, 2005 (0.058 $m^3 \cdot s^{-1}$) and the highest – on the August 9, 2006 (57.92 $m^3 \cdot s^{-1}$). The discharge from the Słup was quite stable, average outflow rate was 2.250 $m^3 \cdot s^{-1}$. The lowest outflows from the reservoir (0.37 $m^3 \cdot s^{-1}$) were recorded in September and October 2005 and November and December 2008 (Fig. 3).

Among the many factors having an impact on the reservoir environment, a significant role is played by the time required for a complete exchange of water in the reservoir (retention time). It not only determines the hydrological state of the reservoir but together with the intensity of water mixing decides on circulation of pollutants in the reservoir, being the factor that has an impact on trophism and quality of the reservoir water [25]. In the literature there are many examples testifying to the great impact of reservoirs on hydrological conditions of the catchment and showing complex structure of the ongoing changes [1-3, 7, 14, 18]. This impact depends first and foremost on the operational capacity of the reservoir against the average annual discharge. The higher this ratio, the easier it is to control the discharge [1]. The average water retention time in the reservoir (Fig. 4) was estimated based on the ratio of the reservoir capacity and the volume of the inflowing water (determined in the investigation period) [26]. The average retention time in the analyzed period was 224.7 days. According to [27], the retention time in big dam reservoirs of potable water is about 1 year. In the case of small reservoirs it varies from one to several dozen days [9].

Based on the analysis of relationship between the volume of water flowing out of the reservoir (Out_res) and water flowing into it (In_res), Pearson's correlation coefficient (r=0.69859) and an equation of regression line Out_res =0.09914+0.48669 · In_res were calculated, the parameters of which were determined using the least-squares method. Between Out_res and In_res there is a high correlation (0.5<(r)<0.7) (this relationship is statistically significant for the significance level p<0.05).

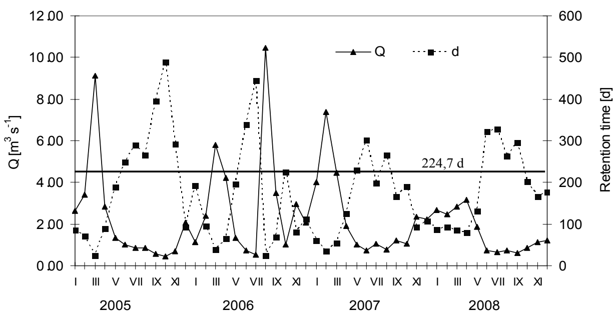

Fig. 4. Relationship between the amount of water flowing into the Słup Reservoir and reservoir capacity in a given time vs. changeability of the retention time, 2005-08.

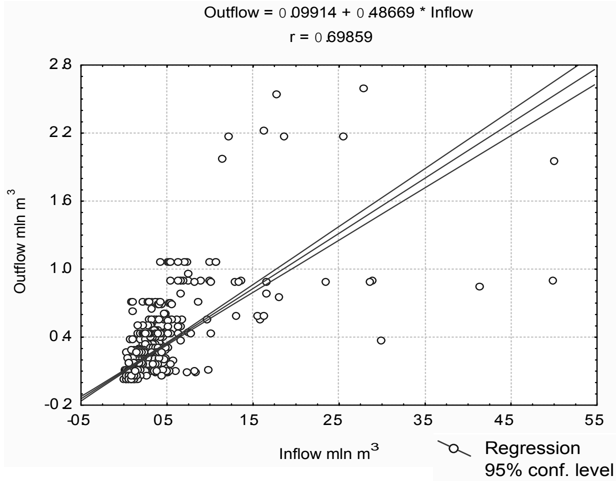

Fig. 5. Graphical presentation of the correlation between the volume of outflowing and inflowing water in the Słup Reservoir (Out_res and In_res), 2005-08.

Fig. 5 presents a graph of the regression line for the volume of outflowing water Out_res vs. volume of water flowing into the reservoir In_res. The confidence level was 95% and marked with external lines. The area between them is the confidence area for the regression line.

Water Quality in the Nysa Szalona River and Słup Reservoir

Results of water quality analyses for water flowing into and out of the Słup Reservoir and water stored in the reservoir are presented in Table 1.

From Table 1 it can be concluded that for most of the analyzed indicators the highest average concentrations were observed in the water flowing into the Słup (In_res). This refers to: nitrates, phosphates, BOD_5, dissolved oxygen, chlorides, sulfates, electrolytic conductivity, and total suspended solids.

In the reservoir water (W_res) the highest average concentration was recorded in the investigated period for the following indicators: COD, TOC, and water temperature. In most cases higher average values corresponded with higher values of the interval and standard deviation and higher confidence levels for the average.

The assessment of the usability of water flowing out of the Słup Reservoir for consumption purposes showed that the values of nitrates, BOD_5, COD, chlorides, sulfates, conductivity, water temperature, and total suspended solids did not exceed the limit values for A1 category (i.e. for water requiring simple physical treatment) [21]. The values of ammonia and total organic carbon qualified the analyzed water as A2, i.e. water requiring typical physical and chemical treatment. Limit values for A3 category, i.e. water requiring efficient physical and chemical treatment were exceeded with regard to phosphates (May 2008) and BOD_5 (June 2008). In other months the indicators did not exceed the limit values defined for the A2 category [21].

Table 1. Characteristics of water flowing into the Słup Reservoir (In_res), reservoir water (W_res), and outflowing water (Out_res), 2005-08.

Water quality indicators	Sampling point	Value			Range	Standard deviation	95% confidence level for the average	
		Min.	Max.	Average			Lower limit	Upper limit
Nitrates (mg $NO_3^-\cdot dm^{-3}$)	In_res	4.90	43.00	22.51	38.10	8.94	19.34	25.69
	W_res	2.60	27.00	12.00	24.40	8.64	7.84	16.17
	Out_res	1.70	29.00	11.52	27.30	8.62	7.36	15.67
Nitrites (mg $NO_2^-\cdot dm^{-3}$)	In_res	0.016	0.260	0.090	0.24	0.06	0.70	0.11
	W_res	0.018	0.026	0.085	0.24	0.08	0.02	0.15
	Out_res	0.020	0.030	0.120	0.28	0.11	0.03	0.19
Ammonia (mg $NH_4^+\cdot dm^{-3}$)	In_res	0.026	0.400	0.13	0.37	0.10	0.096	0.166
	W_res	0.026	0.360	0.15	0.33	0.10	0.085	0.183
	Out_res	0.026	0.510	0.16	0.48	0.14	0.093	0.224
Phosphates (mg $PO_4^{3-}\cdot dm^{-3}$)	In_res	0.13	1.70	0.43	1.57	0.29	0.32	0.53
	W_res	0.05	1.11	0.31	1.06	0.26	0.18	0.43
	Out_res	0.05	1.11	0.30	1.06	0.26	0.17	0.42
BOD_5 (mg $O_2\cdot dm^{-3}$)	In_res	1.0	13.00	3.65	12.00	2.82	2.60	4.70
	W_res	1.0	10.00	3.53	9.00	2.51	2.14	4. 92
	Out_res	1.0	11.00	2.66	10.00	2.41	1.37	3.94
COD_{Mn} (mg $O_2\cdot dm^{-3}$)	In_res	1.80	5.70	3.43	3.90	1.27	2.73	4.14
	W_res	3.50	7.00	4.46	3.50	1.05	3.65	5.26
	Out_res	3.20	4.60	3.73	1.40	0.48	3.36	4.11
DO (mg $O_2\cdot dm^{-3}$)	In_res	8.33	14.00	11.42	5.67	1.83	10.69	12.14
	W_res	8.80	15.00	11.09	6.20	1.76	10.03	12.15
	Out_res	9.00	13.20	10.53	4.20	1.16	9.83	11.24
Chlorides (mg $Cl^-\cdot dm^{-3}$)	In_res	26.30	43.70	35.57	17.40	6.16	31.85	39.29
	W_res	26.00	34.00	28.85	8.00	2.44	27.10	30.59
	Out_res	25.20	30.50	28.55	5.30	1.89	27.19	29.90
Sulfates (mg $SO_4^{2-}\cdot dm^{-3}$)	In_res	54.00	96.00	77.69	42.00	13.66	69.43	85.95
	W_res	50.00	122.00	72.80	72.00	28.75	37.09	108.50
	Out_res	35.00	122.00	68.20	87.00	32.41	27.95	108.45
TOC (mg $C\cdot dm^{-3}$)	In_res	2.80	6.70	3.75	3.90	1.10	3.11	4.38
	W_res	4.40	6.70	5.18	2.30	1.03	3.52	6.82
	Out_res	4.50	5.00	4.72	0.50	0.26	4.30	5.14
Electrolytic conductivity (µs/cm)	In_res	310	641	503.47	331	76.81	474.78	532.15
	W_res	365	415	392.58	50	13.69	385.98	399.18
	Out_res	387	431	404.89	44	12.29	398.97	410.82
Water temperature (°C)	In_res	0.00	25.90	9.41	25.90	6.55	7.08	11.73
	W_res	2.60	26.00	12.70	23.40	6.78	9.43	15.97
	Out_res	3.00	18.60	11.05	15.60	5.14	8.58	13.53
TSS (mg$\cdot dm^{-3}$)	In_res	5.00	40.00	12.43	35.00	11.02	8.39	16.47
	W_res	5.00	16.00	6.73	11.00	3.63	3.94	9.53
	Out_res	5.00	8.00	5.74	3.00	11.18	4.84	6.65

Table 2. Correlation (Pearson's coefficient) between particular water quality indicators for water flowing into the Słup Reservoir (In_res), 2005-08.

ST_1	NO_3	NO_2	NH_4	PO_4	BOD	COD	DO	Cl	SO_4	TOC	Cond	Temp	TSS
NO_3	1.00												
NO_2	-0.21	1.00											
NH_4	-0.19	0.14	1.00										
PO_4	-0.29	**0.38**	0.11	1.00									
BOD	0.06	0.11	0.06	0.29	1.00								
COD	0.10	0.29	-0.06	-0.42	0.31	1.00							
DO	**0.38**	-0.26	0.04	-0.31	-0.03	-0.03	1.00						
Cl	-0.16	-0.32	0.34	**0.60**	-0.15	**-0.67**	-0.10	1.00					
SO_4	-0.37	-0.31	0.04	**0.63**	-0.51	**-0.72**	-0.42	**0.88**	1.00				
TOC	-0.16	**0.53**	0.25	-0.21	0.40	0.15	-0.17	0.04	-0.08	1.00			
Cond	-0.13	-0.07	0.31	-0.27	**-0.39**	**-0.53**	0.03	**0.98**	**0.91**	-0.08	1.00		
Temp	**-0.48**	**0.53**	-0.25	**0.47**	-0.21	0.03	**-0.64**	-0.08	0.31	0.02	-0.10	1.00	
TSS	-0.28	0.18	-0.12	**0.64**	0.22	**0.60**	-0.17	-0.50	-0.35	0.17	-0.34	**0.36**	1.00

Significance level $p<0.05$ marked with bold.

Table 3. Correlation (Pearson's coefficient) between particular water quality indicators for Słup Reservoir water (W_res), 2005-08.

ST_2	NO_3	NO_2	NH_4	PO_4	BOD	COD	DO	Cl	SO_4	TOC	Cond	Temp	TSS
NO_3	1.00												
NO_2	-0.63	1.00											
NH_4	**-0.64**	0.10	1.00										
PO_4	-0.08	-0.21	-0.11	1.00									
BOD	0.31	-0.49	-0.32	0.40	1.00								
COD	0.19	-0.42	0.09	0.58	0.48	1.00							
DO	0.31	-0.54	0.04	0.25	**0.75**	0.50	1.00						
Cl	**-0.80**	**0.80**	0.40	**0.72**	-0.19	-0.30	-0.16	1.00					
SO_4	-0.84	**0.96**	0.28	0.27	-0.65	-0.15	-0.54	0.84	1.00				
TOC	0.88	-0.16	-0.56	-0.51	0.81	-0.20	0.70	**-0.96**	-0.35	1.00			
Cond	0.26	-0.49	-0.04	0.00	0.12	0.19	0.00	-0.26	0.57	-0.87	1.00		
Temp	0.08	0.02	-0.29	0.17	-0.03	0.48	-0.13	-0.17	0.53	-0.69	0.00	1.00	
TSS	0.28	-0.39	0.05	0.58	0.57	**0.95**	0.57	-0.33	-0.25	-0.23	0.18	0.45	1.00

Significance level $p<0.05$ marked with bold.

The linear correlation analysis between all water quality indicators at particular measurement points is presented in Tables 2, 3, and 4. The analysis shows that some of the indicators were significantly correlated at significance level $p<0.05$.

Table 2 shows that a statistically significant negative correlation was observed in the case of nitrates and temperature. A negative relationship between nitrogen reduction in water and water temperature indicates that microorganisms taking part in changes of this chemical in the inflowing water may play a significant role. A positive significant correlation was observed between NO_3^- and DO. In the case of NO_2^- a positive significant correlation was noticed with PO_4^{3-}, TOC, and temperature. In the case of phosphates, a positive significant correlation was observed with chlorides, sulfates, temperature, and total suspended solids.

Table 4. Correlation (Pearson's coefficient) between particular water quality indicators for water flowing out of the Słup Reservoir (Out_res), 2005-08.

Out_res	NO_3	NO_2	NH_4	PO_4	BOD	COD	DO	Cl	SO_4	TOC	Cond	Temp	TSS
NO_3	1.00												
NO_2	-0.16	1.00											
NH_4	**-0.47**	0.14	1.00										
PO_4	-0.14	-0.08	0.09	1.00									
BOD	-0.12	0.15	**0.71**	0.28	1.00								
COD	-0.51	0.00	0.55	0.28	0.46	1.00							
DO	-0.08	-0.40	0.40	-0.12	-0.07	-0.04	1.00						
Cl	**-0.82**	0.15	**0.65**	0.25	0.20	0.47	0.14	1.00					
SO_4	-0.58	0.39	0.14	**0.75**	-0.88	0.48	**-0.97**	**0.91**	1.00				
TOC	0.24	-0.35	-0.70	0.00	-0.82	-0.64	0.21	-0.48	0.00	1.00			
Cond	0.01	-0.07	0.12	0.03	0.34	0.19	-0.41	-0.23	-0.29	0.43	1.00		
Temp	-0.21	0.12	-0.12	0.11	0.08	-0.09	**-0.92**	-0.29	-0.07	0.32	0.44	1.00	
TSS	-0.30	0.38	0.05	-0.27	0.57	0.24	-0.49	0.40	0.01	-0.89	-0.08	0.23	1.00

Significance level $p<0.05$ marked with bold.

Table 2 also shows that a statistically significant negative correlation was observed for BOD_5 and conductivity. In the case of COD, a significant negative correlation was noted with chlorides, sulfates, and electrolytic conductivity, whereas a positive correlation was observed only with total suspended solids.

As far as Table 3 is concerned, one notices a statistically significant negative correlation in the reservoir water for nitrates and ammonia, and nitrates and chlorides. A positive correlation of nitrites with chlorides and sulfates is observed. The same holds for the correlation of phosphates with chlorides.

Table 4 shows for nitrates a significant negative correlation with ammonia and chlorides. For phosphates a significant positive correlation with sulfates is observed. For phosphates no high and statistically significant correlations with chlorides are noticed in the outflowing water. However, ammonia is highly and significantly correlated with BOD_5 and Cl^-. The ammonia content in water is a key indicator of pollution with albuminous substances that usually occur in high concentrations in wastewater.

Table 5 shows the statistical significance of the differences in observed concentrations (μ) of the physico-chemical indicators between inflowing and outflowing water in the Słup Reservoir. To assess the significance of these differences the Student's t-test for independent samples was used, at a significance level of $p<0.05$. The zero hypothesis H_0 was $\mu_{Inflow}=\mu_{Outflow}$. Since the purpose of the study was to verify whether the reservoir influenced the quality of water, the alternative hypothesis was H_1: $\mu_{Inflow}>\mu_{Outflow}$ or $\mu_{Inflow}<\mu_{Outflow}$.

Based on analysis of concentrations of all water quality indicators for inflowing (In_res) and outflowing (Out_res) water in the reservoir it can be concluded that for three indicators – nitrates, chlorides, and electrolytic conductivity – there are statistically significant differences ($p<0.05$). For the remaining indicators, statistically insignificant differences were observed ($p>0.05$).

Table 5. Statistical significance of the analyzed water quality indicators for inflowing (In_res) and outflowing (Out_res) water of the Słup Reservoir, 2005-08.

Water quality indicators	In_res – inflow to reservoir Out_res – outflow from reservoir		
	t	df	p
Nitrates	4.325	50	**0.000**
Nitrites	- 0.994	39	0.326
Ammonia	- 0.839	50	0.405
Phosphates	1.616	50	0.112
BOD	1.199	44	0.236
COD	- 0.674	22	0.506
DO	1.585	38	0.121
Cl	3.462	21	**0.002**
SO_4	0.898	16	0.382
TOC	-1.726	16	0.103
Electrolytic conductivity	5.528	47	**0.000**
Temp	- 0.940	50	0.351
TSS	1.801	38	0.079

Significance level marked with bold.

From the tests it can be concluded that the Słup Reservoir dam changes the hydrological regime of the Nysa Szalona River, contributing to an increase of the water table and some depth changes. As a result, water temperature went up (from 9.4ºC to 12.7ºC) and its turbidity decreased (from 12.43 to 5.7 mg·dm^{-3}), which facilitated penetration of light required for photosynthesis into the upper layer of the reservoir. If in such conditions the inflow of fertilizing substances to the Słup Reservoir is increased, the process of photosynthesis may intensify, which may result in the development of phytoplankton and zooplankton. Production of plankton is a continuous process that lasts as long as there are enough fertilizing substances. It is also favorable for the reservoir until the intensification of trophy [10, 12, 28]. If the process of photosynthesis and plankton production are very intensive and effective, they may pose a threat to the economic use of the reservoir and its proper operation [9, 29, 30, 31]. According to studies presented in [32], about 50% of inflowing loads of total phosphorus and total nitrogen were accumulated in the Słup Reservoir. The authors found out that the Słup, despite seasonal water "blooming," had a positive impact on the quality of surface waters of the Nysa Szalona River. Research studies of Rzewuska [33] on the quality of water reservoirs located in Poland in the basin of the upper and central Odra River shows that if proper quality of water in the reservoir is to be maintained, the dam reservoirs for which the surface load of nitrogen and phosphorus was calculated (Turawa, Otmuchów, Głębinów, Bukówka, Pilchowice, Leśna, Złotniki, Mietków, Dobromierz, and Słup) showed high exceedence of standards defined by Vollenweider [33].

From [34] it can be concluded that the construction of the reservoir changes hydrological relationships and, consequently, has an impact on biological, chemical, and physical processes taking place in water. Data presented there on trends of water quality changes due to a damming-up process show that in 42% reservoirs improved the quality of water due to damming, in 10% - worsened, in 11% some parameters were improved, whereas in 37% no water quality changes were observed. In the case of the Słup Reservoir a positive impact on the improvement of water quality with regard to selected water quality indicators is observed. The obtained results show that in the investigated period of 2005-08, loads of the following indicators decreased in the reservoir: nitrates by 49%, phosphates by 30%, BOD_5 to about 27%, dissolved oxygen by about 8%, chlorides by 20%, sulfates by 12%, total suspended solids by over 53%, and electrolytic conductivity more than 19%. In the water beneath the reservoir increased concentrations of nitrites (by 33%), ammonia (by 23%), COD (by 8%), organic carbon (to about 26%) and water temperature (by 17%) are observed (Table 1).

Proposal for Protection of the Słup Reservoir by Construction of a Pre-Dam

Since the main function of the Słup Reservoir is providing drinking water, the quality of water is very important. In order to check to what extent the reservoir is exposed to eutrophication, some calculations were made for 2005-08. Based on Vollenweider's criterion [35], in Benndorf's modification [36], and taking into account the fact that the concentration of phosphates in the cross-section of the future reservoir is 0.43 mg PO_4^{3-}·dm^{-3} (Table 1), it has been discovered that the amount of phosphorus per 1 m^2 of the reservoir is 3.81 g P-PO_4·m^{-2}·a^{-1} at the ratio of the average reservoir depth of 7.6 m (assumed for the period of 2005-08) to retention time – 0.276 a. The load of inorganic nitrogen flowing into the reservoir is computed as 384.3 t N·a^{-1}. Therefore, the Słup Reservoir must be classified as a polytrophic lake. It must be stressed here that calculations referred only for phosphorus and nitrogen from tributaries – direct catchment and internal load from sediments were not taken into consideration. To protect the Słup Reservoir from pollutants flowing from the Nysa Szalona catchment, construction of a pre-dam in the reservoir backwater has been proposed (Fig. 1). The reduced volume of water stored in the reservoir will be partially compensated by the additional volume of water stored in the pre-dam. According to the literature, pre-dams have many functions: they serve as an additional water reservoir, stop suspended solids, bed loads and fertilizing substances, contribute to biodegradation of organic pollutants supplied from the catchment, protect the main reservoir from emergency discharge of pollutants (which is particularly important in the case of a water supply reservoir) and protect from uncovering a part of the reservoir in backwater [9, 15, 16, 37, 38]. Effectiveness of the pre-dam as described by [16] is 65% for nitrates and 53% for phosphates.

Nowadays the area of the designed pre-dam is covered by meadows and idle lands. The area is seasonally watered when the fill level in the Słup Reservoir goes above 174.00 m a.s.l. For the pre-dam a flap weir at the inlet to the reservoir is proposed. A similar solution was applied in the Turawa Reservoir, where the pred-dam "Jedlice" was separated from the main reservoir by a flap weir [39]. The weir facilitates aeration of water flowing out of the pre-dam. Additionally, the use of a bio-filter in the pre-dam is recommended. The bowl of the pre-dam must be shaped properly so that water vegetation could develop. The depth of the water should be up to 3 m and the average flow rate 0.05-0.3 m·s^{-1} [9, 16]. In such a bowl macrophytes should be planted [16]. Conditions in the Słup Reservoir backwater allow for the construction of the pre-dam with a capacity of up to 4 mln m^3. Its area could be about 130 ha.

Conclusions

Analyses carried out in the Słup Reservoir in the period of 2005-08 shows that:

1. The reservoir has an impact of water flows in the Nysa Szalona River.

a) In the analyzed period the normal operational fill level NPP=174.00 m a.s.l. was slightly exceeded in three short periods, due to increased inflows to the reservoir in the overflow periods. The average water fill ordinate in this period was lower than the NPP ordinate assumed in the guidelines on water management (Fig. 2).

b) The analysis of the inflowing water showed that the average water inflow to the reservoir was 2.265 m^3/s, whereas the average water outflow from reservoir was 2.250 $m \cdot s^{-1}$. This, indicates however, that the reservoir considerably compensated the flows of the Nysa Szalona River (Fig. 3).

c) The average volume of water stored in the Słup Reservoir was lower than the one assumed for the reservoir in the guidelines on water management. The water table variation amplitude in the reservoir in the analyzed period was 4.33 m (Fig. 2) and the average water retention time was 224.7 days (Fig. 4).

d) There is a statistically significant correlation between the volume of water flowing out of the Słup O-zb and the inflowing water D-zb (r=0.69). The relationship was described using an equation of the regression line: Out_res =0.09914+0.48669 · In_res (Fig. 5).

2. The Słup contributes to the improvement of water quality in the Nysa Szalona River.

a) Changes of average physico-chemical indicators of inflowing, outflowing, and reservoir water were observed. In the inflowing water (In_res) the highest average concentrations of the following parameters were observed: nitrates, phosphates, BOD_5, dissolved oxygen, chlorides, sulfates, electrolytic conductivity, and suspended solids (Table 1). Only three of these parameters are shown to be statistically significant (Nitrates, Cl, and electrolytic conductivity).

b) At particular measurement points high, statistically significant correlations between selected water quality indicators were observed (Tables 2-4).

c) From the analysis of all water quality indicators for water flowing into the reservoir (In_res) and the outflowing water (Out_res), it can be concluded that there are statistically significant differences ($p<0.05$) for nitrates, chlorides, and electrolytic conductivity (Table 5).

3. To protect the Słup Reservoir from the inflowing pollutants from the catchment of the Nysa Szalona River, construction of the pre-dam in the backwater of the reservoir is proposed. The pre-dam will contribute both to the improvement of the quality of water flowing into the main reservoir but also – to some extent – will compensate for the volume of water stored in the reservoir and reduced by lowering the water fill ordinate.

References

1. KRZANOWSKI S. The influence of reservoir retention on selected environmental elements with particular consideration given to the changes in downstream discharge regimes (a case study of the San river basin), Zesz. Nauk. AR w Krakowie, Rozprawy, **259**, 156, **2000** [In Polish].
2. HORN W., HORN H., GEIGER D., PAUL L. Consequences of the flood in August 2002 to the water quality in the Saidenbach reservoir [In]: Tagungsbericht der Deutschen Gessellschaft für Limnologie, Köln, pp. 684-689, **2003**.
3. CIEPIELOWSKI A. Rudiments of water management. SGGW, Warszawa, pp. 326, **1999** [In Polish].
4. MIODUSZEWSKI W. Small water reservoir. Designing guidelines. IMUZ, Falenty, pp. 30, **2008** [In Polish].
5. CZAMARA W., ROSIK-DULEWSKA CZ., WIATKOWSKI M., FRYCZ K. The role of Racibórz water reservoir in flood protection of Odra Valley. [In]: Crisis management - flood protection (scientific research). Ed. by W. Czamara, A. Dubicki, M. Wiatkowski, Uniwersytet Opolski, Opole, pp. 173-188, **2008** [In Polish].
6. GRELA J., STOCHLIŃSKI T. Analysis of the operation of storage reservoirs in the tributary of the upper Wisła River during flood in July 2001. Gosp. Wod. **2**, 74, **2002** [In Polish].
7. WIATKOWSKI M., ROSIK-DULEWSKA CZ., JESIONEK B. Analysis of water management of Słup Reservoir on Nysa Szalona river. Zesz. Probl. Post. Nauk Roln., **2009** in print [In Polish].
8. SIEBER H.U. Reservoirs as multifunctional systems. WWT, **12**, 17, **2003**.
9. WIATKOWSKI M., CZAMARA W., KUCZEWSKI K. Influence of pre-dams on changes of quality of the retention waters in main reservoirs. Institute of Environmental Engineering of the Polish Academy of Science, Zabrze, pp. 122, **2006** [In Polish].
10. DOJLIDO J. R. Chemistry of surface waters. Wyd. Ekonomia i Środowisko, Białystok, pp. 343, **1995** [In Polish].
11. GOŁDYN R. Changes in biological and physico-chemical parameters of river water quality as a result of its damming in preliminary lowland reservoirs. Wyd. Nauk. UAM, Poznań, pp. 185, **2000** [In Polish].
12. KAJAK Z. Hydrobiology – Limnology. Inland water ecosystems. PWN, Warszawa, pp. 360, **2001** [In Polish].
13. JEKATIERYNCZUK-RUDCZYK E., GÓRNIAK A., ZIELIŃSKI P., DZIEMIAN J. Daily dynamics of water chemistry in a lowland polyhumic dam reservoir. Polish Journal of Environmental Studies **11**, (5), 521, **2002**.
14. SUCHOWOLEC T., GÓRNIAK A. Changes of water quality in small reservoirs in agricultural landscape of northern Podlasie. Teka Kom. Ochr. Kszt. Środ. Przyr. **3**, 195, **2006**.
15. PAUL L., PÜTZ K. Suspended matter elimination in a pre-dam with discharge dependent storage level regulation. Limnologica, **38**, 388, **2008**.
16. CZAMARA W., CZAMARA A., WIATKOWSKI M. The use of pre-dams with plant filters to improve water quality in storage reservoirs. Arch. Environ. Protect., **34**, 79, **2008**.
17. WIATKOWSKI M., PAUL L. Surface water quality assessment in the Troja river catchment in the context of Włodzienin Reservoir construction. Polish J. of Environ. Stud. **18**, (5), 923, **2009**.
18. KOSIERB R., JESIONEK B. Effectiveness of the Słup storage reservoir in flood overflow and low flow periods. Nationwide symposium hydrotechnics Symp. Ogólnokrajowe Hydrotechnika VII, Katowice, pp. 251-262, **2005** [In Polish].
19. Materials of the Regional Water Management Board in Wrocław on water management in the Słup reservoir. Typescript, Wrocław, **2009** [In Polish].
20. Voivodeship Inspectorate of Environmental Protection in Wrocław, Legnica Branch – Results of water quality analysis for the Nysa Szalona River and Słup Reservoir, Legnica, **2009** [In Polish].
21. Ordinance of the Ministry for the Environment dated 27 November on requirements for surface waters used for consumption. Polish Journal of Laws 2002, No. **204**, item 1728, pp. 14, **2002** [In Polish].

22. KALA R. Statistics for nature scientists. AR w Poznaniu, Poznań, pp. 232, **2002** [In Polish].
23. WĄTROBA J. (Ed.). Statistics and data meeting in scientific research. StatSoft Polska, Kraków, pp. 112, **2006** [In Polish].
24. Guidelines for operation and water management in the Słup storage reservoir. Typescript, Hydroprojekt Spółka z o.o. Wrocław, pp. 94, **2002** [In Polish].
25. BAJKIEWICZ-GRABOWSKA E. Circulation of master in the river-lake systems, Warsaw University, Faculty of Geography and Regional Studies, Warszawa, pp. 274, **2002** [In Polish].
26. STRAŠKRABA M., HOCKING G. The effect of theoretical retention time on the hydrodynamics of deep river valley reservoirs. Inter. Rev. Hydrobiol. **87**, (1), 61, **2002**.
27. UHLMANN D., HORN W. Ecology of dams. Habitats, organisms, spatial and temporal structures. Biol. Unserer Zeit, **36**, 92, **2006**.
28. ILNICKI P. Surface water eutrophication – process, reasons, and sources. Przegl. Kom. **2**, (125), 35, **2002** [In Polish].
29. PÜTZ K., BENNDORF J. Purpose-oriented water quality management of reservoirs and dam plants – Information to the technical standard TGL 27885/03. Acta hydrochim. et hydrobiol., **9**, 25, **1981**.
30. DIOGO P.A., FONSECA M., COELHO P.S., MATEUS N.S., ALMEIDA M.C., RODRIGUES A.C. Reservoir phosphorous evaluation and water quality modeling in a transboundary watershed. Desalination **226**, 200, **2008**.
31. OSTOJIČ A., ĆURČIĆ S., ČOMIĆ L., TOPUZOVIĆ M. Estimate of the eutrophication process in the Gruža Reservoir (Serbia and Montenegro). Acta hydrochim. hydrobiol. **33**, (6), 605, **2005**.
32. CZAMARA W., KRĘŻEL J., ŁOMOTOWSKI J. Impact of reservoir storage on surface water quality in the catchment of Nysa Szalona River. Zesz. Nauk. AR we Wrocławiu, Konf. III, **2**, **246**, 53, **1994** [In Polish].
33. RZEWUSKA E., SZYJKOWSKI A., MARCHLEWSKA-KNYCH B. Characteristics of surface stagnant water resources in the tributary of upper and central Odra River. Zesz. Nauk. AR we Wrocławiu, Inż. Środ. III, **232**, 139, **1993** [In Polish].
34. WOYCIECHOWSKA J., DOJLIDO J. Hydrotechnical structures and changes in surface water quality. Gosp. Wod., 5, **1982** [In Polish].
35. VOLLENWEIDER R. A. Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem. Ist. ital. Idrobiol. **33**, 53, **1976**.
36. BENNDORF J. A contribution to the phosphorus loading concept. Int. Revue ges. Hydrobiol. **64**, 177, **1979**.
37. BENNDORF J., PÜTZ K. Control of eutrophication of lakes and reservoirs by means of pre-dams – I. Mode of operation and calculation of the nutrient elimination capacity. Wat. Res. **21**, 829, **1987**.
38. BENNDORF J., PÜTZ K. Control of eutrophication of lakes and reservoirs by means of pre-dams – II. Validation of the phosphate removal model and size optimization. Wat. Res. **21**, 839, **1987**.
39. WIATKOWSKI M., CZERNIAWSKA-KUSZA I. Use of Jedlice preliminary reservoir for water protection of Turawa dam reservoir. Oceanological and Hydrobiological Studies, **XXXVIII**, (1), 83, **2009**.